A STUDY OF HIGH POWER ARGON LASER OPTICS

INTERIM SCIENTIFIC REPORT

Contract NAS 12-548

by

George deMars

Michael Seiden

and

Frank Horrigan

RAYTHEON COMPANY
Research Division
Waltham, Massachusetts

NOVEMBER 1967

Prepared for
Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

S-1015

A STUDY OF HIGH POWER ARGON LASER OPTICS

By George deMars, Michael Seiden, and Frank Horrigan

Interim Scientific Report
April 15, 1967 to October 31, 1967

November 1967

Prepared under Contract No. NAS 12-548 by
RAYTHEON COMPANY, RESEARCH DIVISION
Waltham, Massachusetts

Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED.

LIST OF ILLUSTRATIONS

A STUDY OF HIGH POWER ARGON LASER OPTICS

By George deMars, Michael Seiden, and Frank Horrigan

SUMMARY

The recent development of high power, continuous duty, argon lasers has produced optical power levels, within the laser cavity, in excess of 1 kW/cm^2. Optical components have shown degradation or failure at such power levels, particularly when exposed to the environment of the high current density, ionized gas discharge. The critical optical interface is located at the surface which terminates the discharge tube. A layer develops at this surface which absorbs a fraction of the power present, sufficient to result in thermal distortion.

Various studies were started to observe and understand the nature of optical degradation of mirrors and windows exposed to high levels of optical power. The thermal distortion of windows has been documented and correlated with theory. Mirror studies have been empirical.

INTRODUCTION

The construction of ionized argon discharge structures capable of continuous operation with circulating cavity power densities in excess of 1 kW/cm^2 revealed deficiencies in the capability of the optical components to accommodate such power levels. The multiple dielectric mirrors available at that time not only became thermally distorted during laser operation but often suffered permanent damage in the form of film "bleaching" or actual film disruption.[1] A component which proved to be a source of more serious power limitation was a Brewster's angle window used to terminate the discharge tube. With such a termination laser output was observed to decay at a rate which varied with the level of operation. A shrinking of the beam size and change in mode configuration was observed to be coincident with this power decay.

The investigation of the nature and cause of optical component failure under conditions of high power was undertaken in order to exploit the advances in high density ionized argon discharge tube construction. Where indicated, remedial measures will be tried with a view toward eventual attainment of argon laser, single transverse mode output power levels in excess of 30 W.

Optical component tests in this study were made utilizing a large ionized argon discharge structure which, when operated as a laser, has an output power capability approaching 100 W. With this structure, component behavior was observed at high power levels under practical laser operating conditions.

Experiments to date have been directed primarily toward understanding the nature of optical window degradation. Methods of identifying and measuring the extent of window degradation were developed. The extent and rate of degradation was determined for various cavity configurations and discharge operating levels. Attempts were made to modify the process.

An evaluation of state-of-the-art dielectric-coated mirrors for use in high output power operation was started. The optical coating industry has been responding to the demands imposed by the high power densities attainable with ionized argon lasers. Many aspects of the ability of mirrors produced more recently to withstand optical power densities in excess of 1 kW/cm^2 were reported shortly after this investigation began.[2] The present study is directed toward achieving maximum output power with available coatings. Test results were obtained using greater than optimum output coupling values to reduce the internal cavity power level.

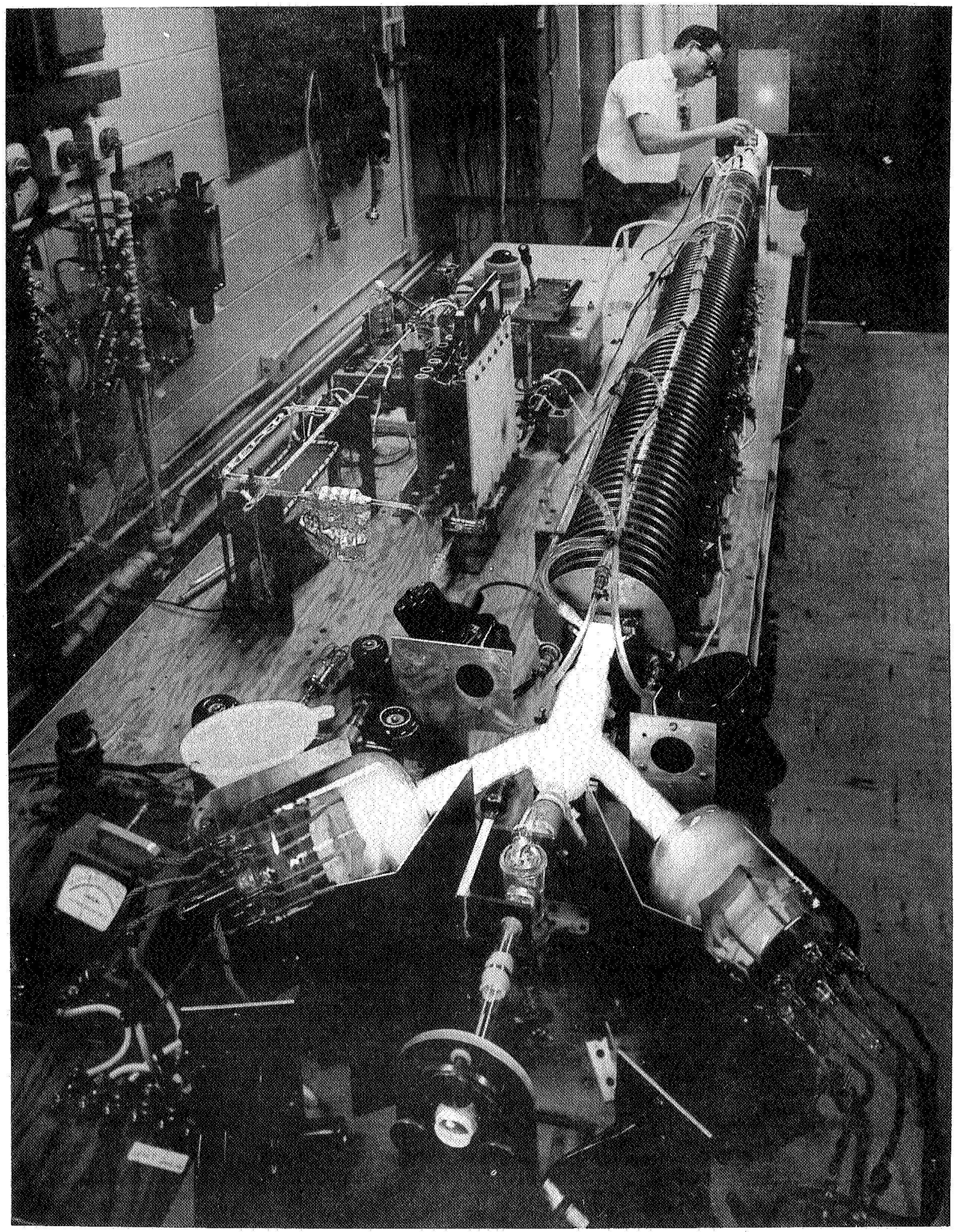
APPARATUS AND MATERIALS

Laser Structure

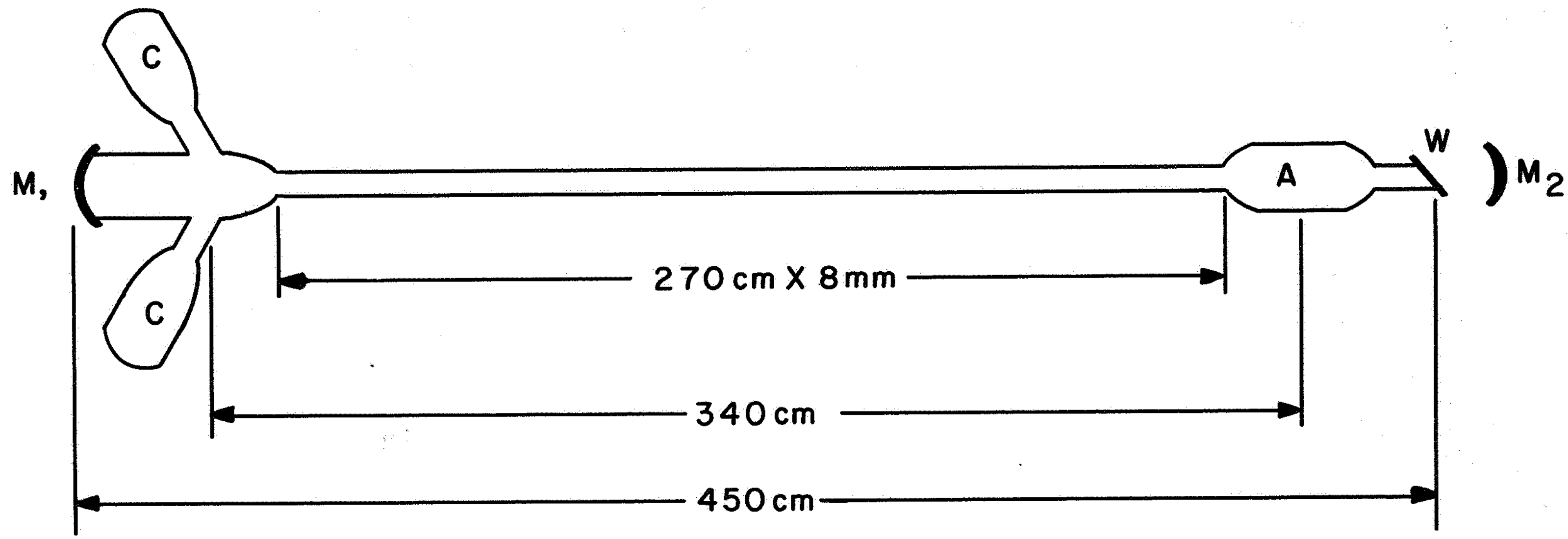
The discharge structure used for most of the work performed to date is shown in Fig. 1. The ionized argon discharge is produced in a water-cooled quartz tube about 270 cm long and 8 mm in diameter. The multiple, oxide-coated, tungsten mesh cathodes have a total rated capacity of 200 A. A remote power supply rated at 200 A and 750 V provides high current operation of the tube. Axial magnetic fields up to 1 kOe are provided by solenoids encompassing the length of the tube. Large bore, in-line stopcocks are used in conjunction with a large capacity pumping system to provide isolation of the terminal optics, which permits rapid, easy interchange of the optics without disturbing the electrodes. A typical optical cavity configuration is shown schematically in Fig. 2. The optics are mounted, using O-ring seals, on a positioning structure connected by metal bellows to the discharge tube. A more detailed view of the valving and tuning arrangement at the anode end of the discharge structure is shown in Fig. 3. Some details of the Brewster's angle window and internal mirror mounts are indicated in Fig. 4 at parts A and C. The windows are held on the polished face of the Brewster's angle cut with high viscosity vacuum grease, Apeizon H. For the purpose of this investigation this structure is denoted as the principal laser.

Optical Flats

The optical flats used in this study for Brewster's angle windows were obtained from a number of vendors. All of these were fabricated



THE PRINCIPAL LASER
FIGURE I



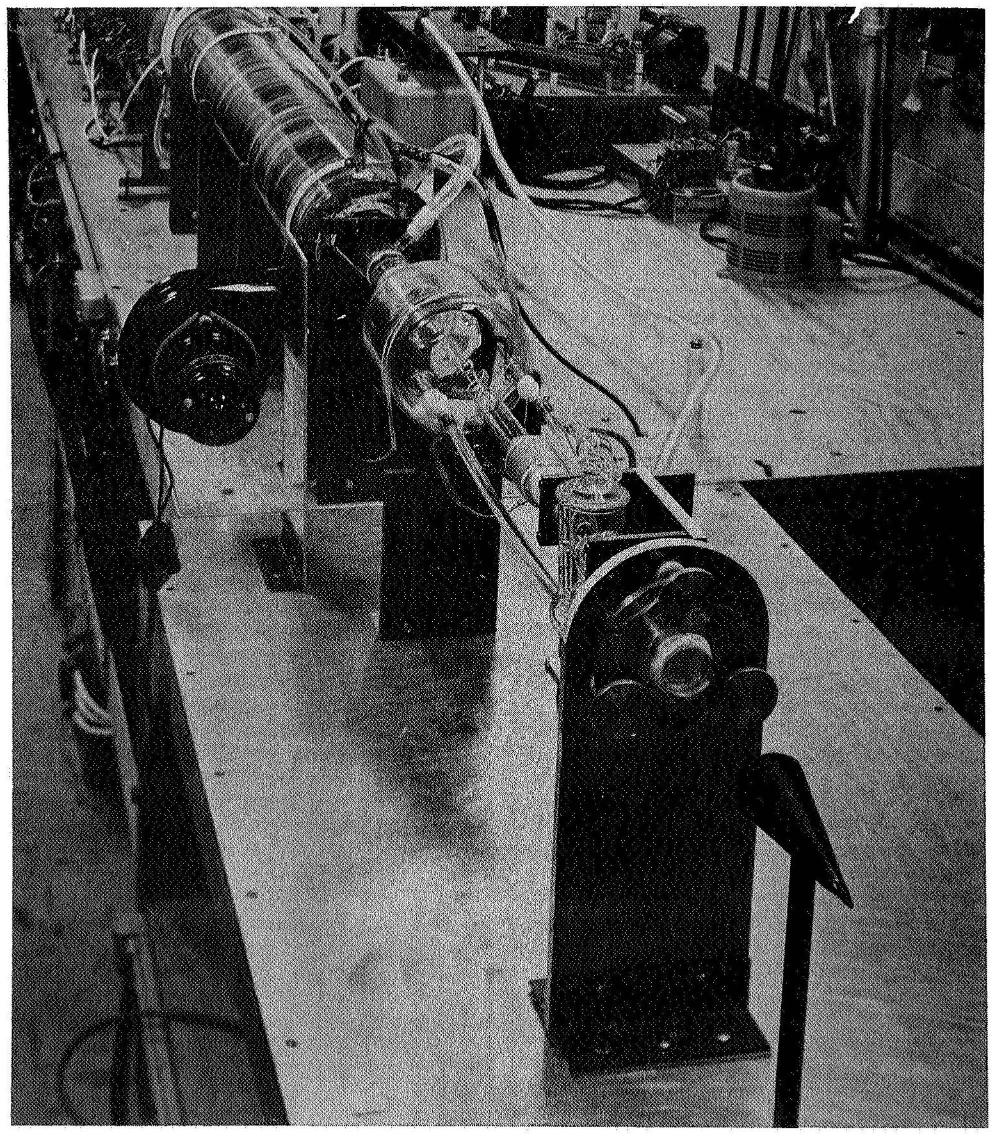
M_1 —100 % R, 366 cm radius

M_2 —92% R, 366 cm radius

C – cathode
A – anode
W – test window

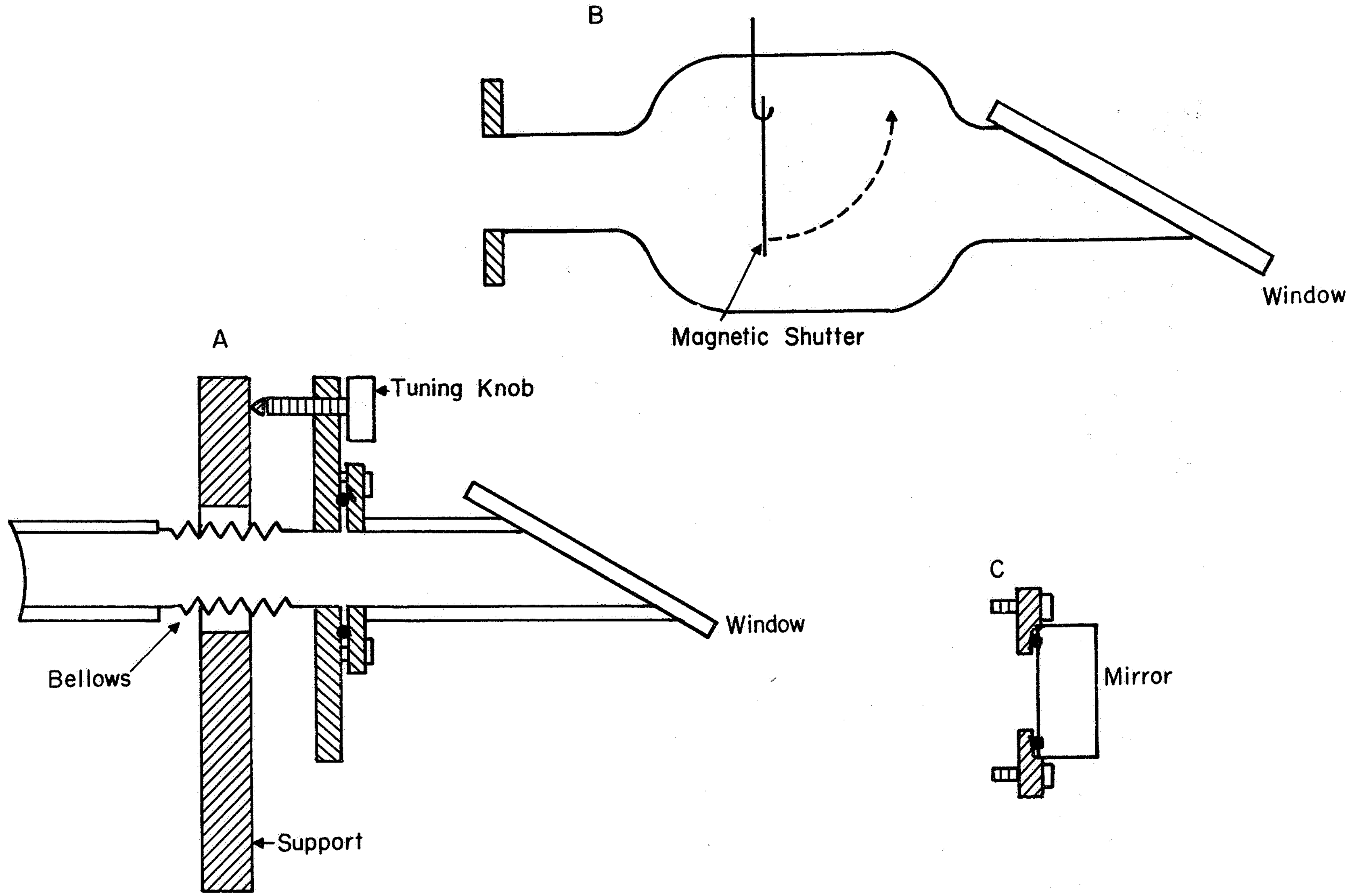
SCHEMATIC OF ARGON LASER

FIGURE 2



ANODE END OF PRINCIPAL LASER; STOPCOCK
AND TUNABLE MOUNT FOR VACUUM OPTICS

FIGURE 3



VACUUM WINDOW AND MIRROR MOUNTS

FIGURE 4

from highest optical grade, fused quartz (e.g., Suprasil grade from Amersil Inc.) and were specified to be flat to better than 1/10 wave with a minimum scatter finish.

Initially the effect of window behavior on high power laser operation was observed by monitoring the output power, the beam geometry, and the optical figure of the window. This last condition was noted by producing a shearing interferogram using a helium-neon laser in an arrangement indicated schematically in Fig. 5. The argon laser beam geometry was recorded by photographing the output, suitably expanded by a simple lens. The output power was monitored using a calorimeter and chart recorder. After a correlation was established among these observations of window distortion and beam power and geometry, the usual procedure was to record only the decay of the output power while testing the effects of novel geometries such as the shutter arrangement illustrated in Fig. 4 at part B.

Mirrors

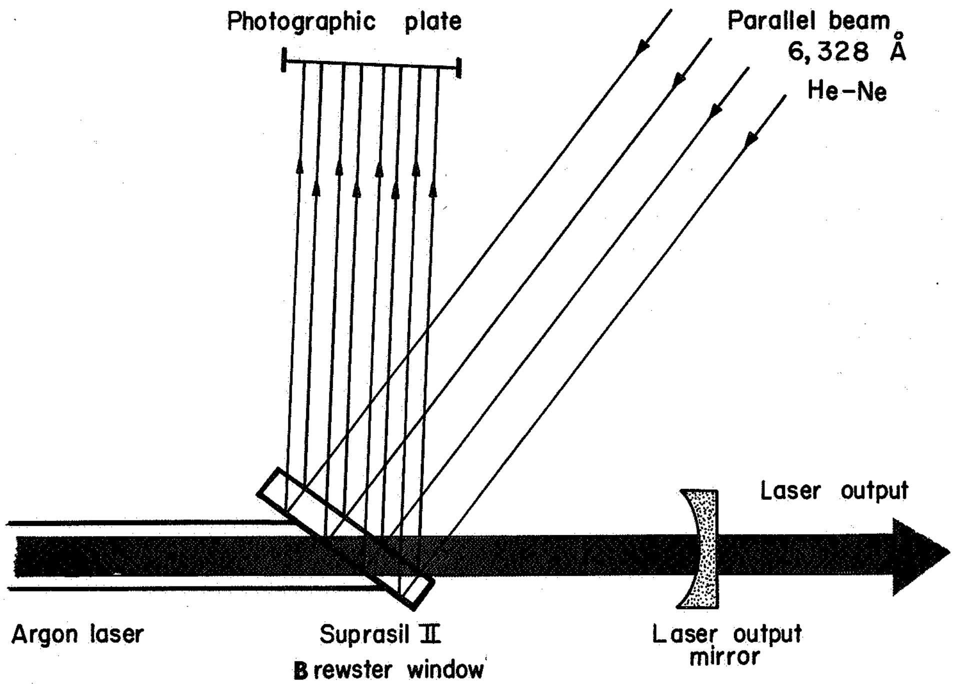
All mirrors used to date were made of multilayer, dielectric coatings on fused quartz substrates. Three different radii of curvature of 3.7, 6.6, and 10m, all finished to at least 1/10 wave, were employed in pairs of similar geometry. Most of the mirror testing, however, was done with 3.7 m radius mirrors. The dielectric coatings were provided by various vendors. Mirror-coating evaluation to date has generally been limited to observing the variations of laser output beam geometry, power, and stability as a function of input power. Bulk heating of the substrates and the surface scatter of the coatings were also investigated, as well as such changes as could be noted by visual inspection.

TEST RESULTS

Degradation of the Windows

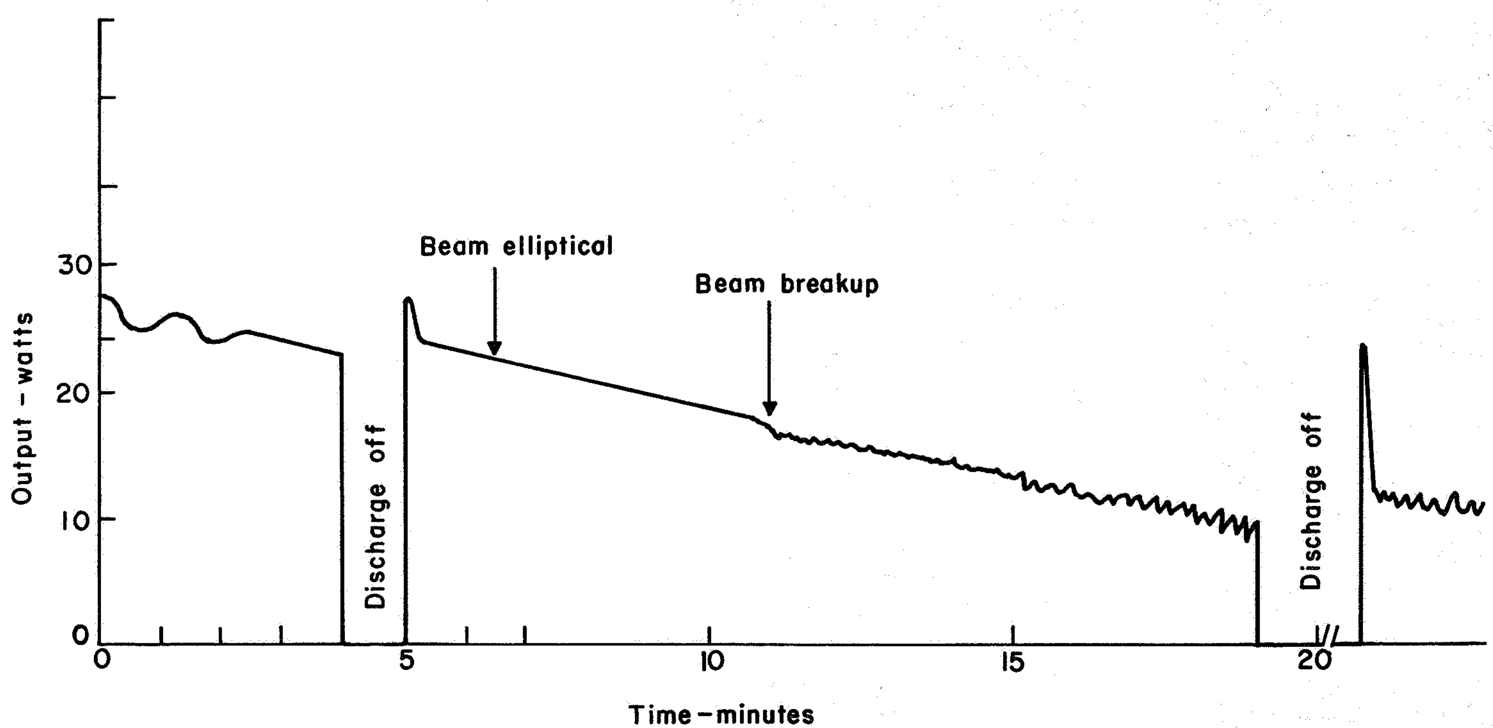
The salient features of Brewster's angle window degradation and its interaction with the laser cavity oscillation are comprehensively documented in Figs. 6, 7, and 8. In Fig. 6 the decay of laser output power with time is indicated, in Fig. 7 representative samples of output beam geometry are presented, and in Fig. 8 visual evidence of the thermal distortions of the window is presented. Although these data were obtained from different test runs, collectively they illustrate the qualitative aspects of high power operation with Brewster's angle windows. The features depicted in Figs. 6–8 are always present with window degradation, only the time scale, which may range from seconds to hours, varies according to discharge operating parameters and the previous history of the discharge structure.

As shown in the data, window degradation results initially in a drop in output power accompanied by a reduction in beam diameter. As the power



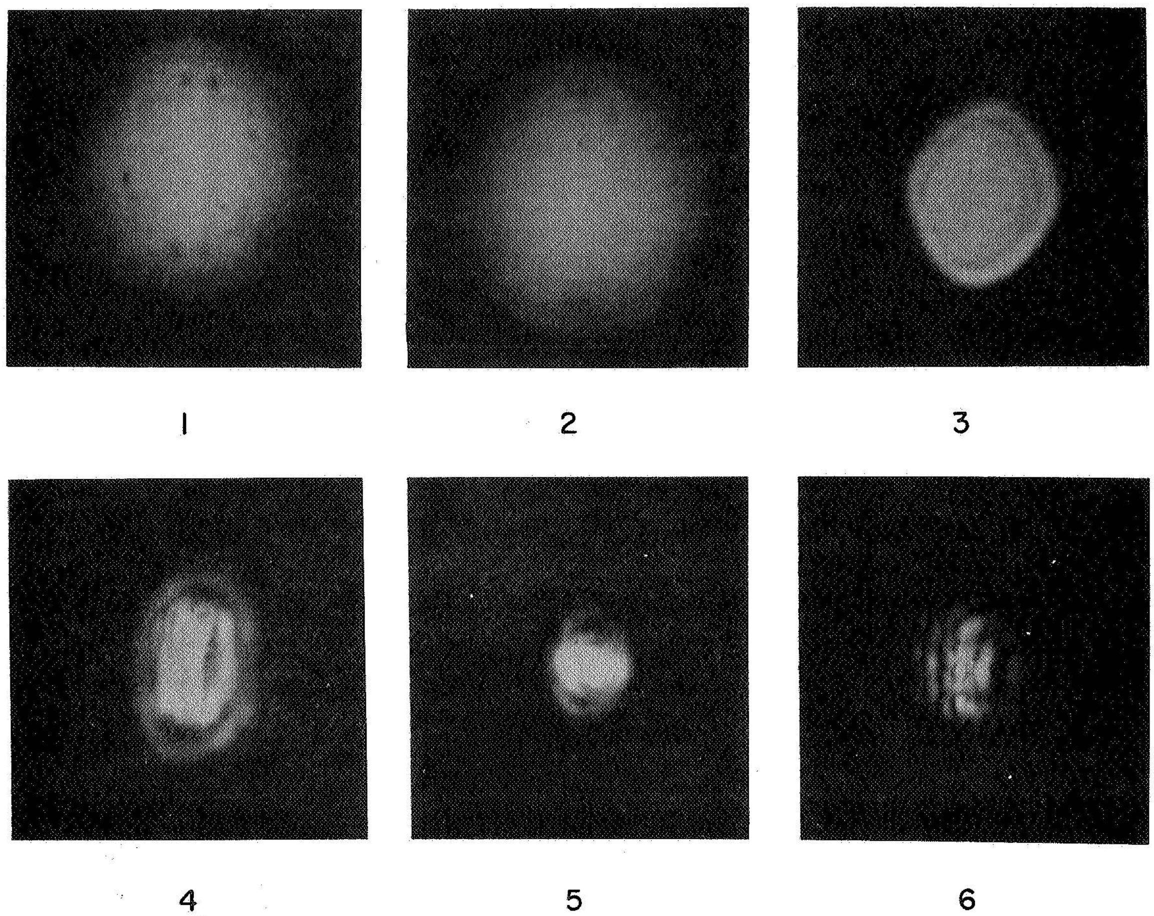
ARRANGEMENT OF APPARATUS FOR OBTAINING SHEARING INTERFEROGRAMS OF BREWSTER'S ANGLE WINDOW

FIGURE 5



TYPICAL DECAY OF OUTPUT POWER DUE TO WINDOW DEGRADATION. DISCHARGE CURRENT IS 70 AMPERES.

FIGURE 6



MODE DISTORTION OF ARGON LASER
(70 A Discharge)

1 Laser turned on 15 W output

2 After 1 minute 10 W output

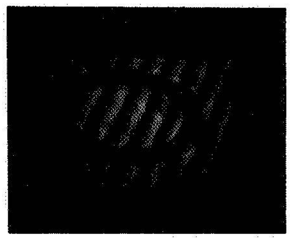
3 After 5 minutes 9.3 W output

4 After 10 minutes 7.5 W output

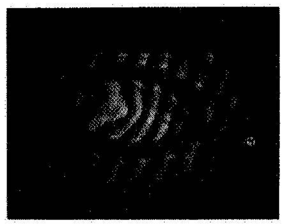
5 After 20 minutes 6.5 W output

6 After 35 minutes 5 W output

FIGURE 7



Laser off



70 amp discharge 10 watts output after 1 minute

70 amp discharge 5 watts output after 35 minutes

SHEARING INTERFEROGRAMS OF BREWSTER'S
ANGLE WINDOW DURING LASER OPERATION

FIGURE 8

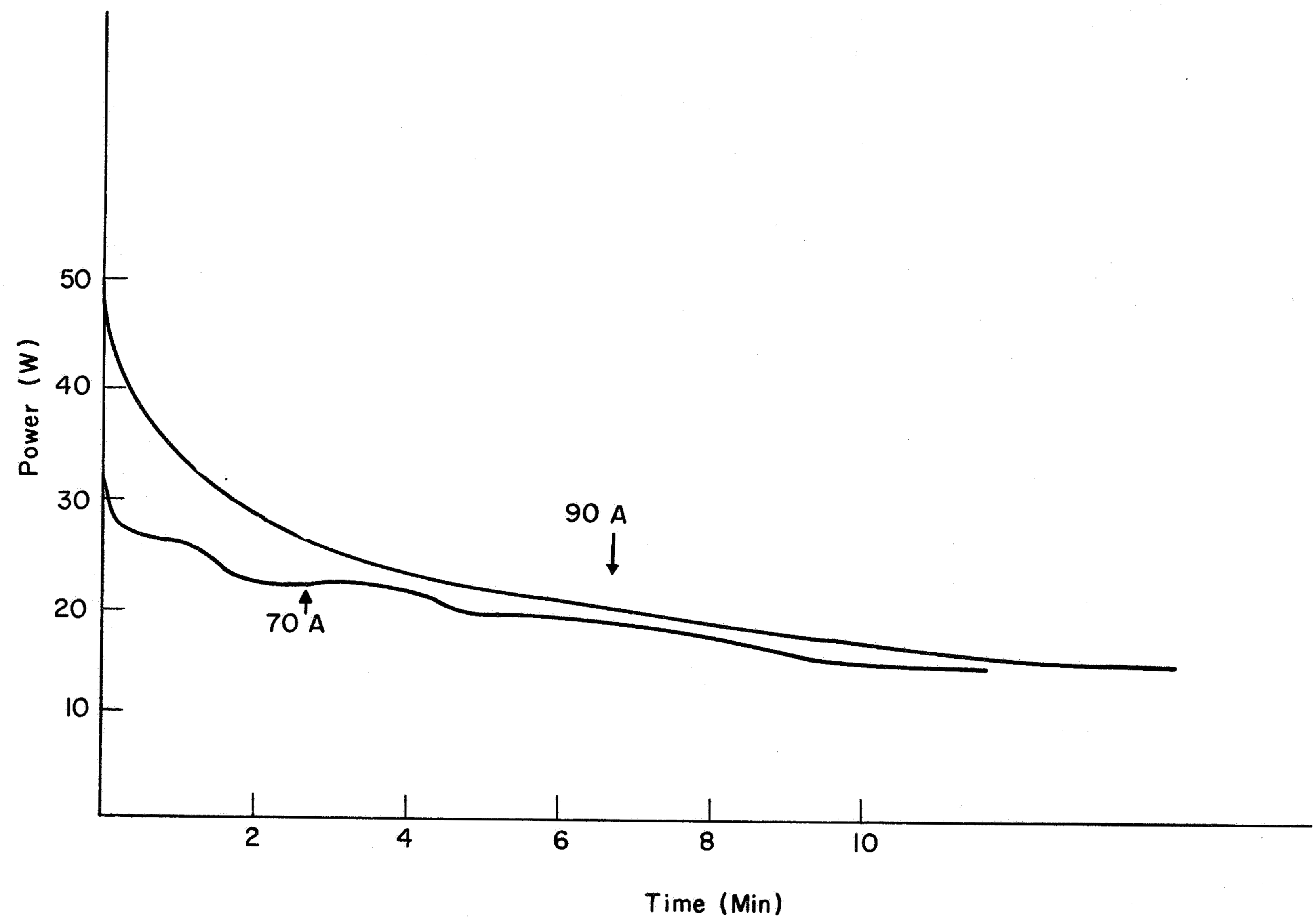
continues to decline, the beam geometry changes from a circular to an elliptical pattern which continually shrinks in area. The series of six beam photographs in Fig. 7 illustrates this change in beam geometry. The second interferogram in Fig. 8 indicates that a local lenticular deformation of the inner surface of the window accompanies the changes in beam geometry. As this deformation becomes more severe, the beam continues to shrink until there is an abrupt change in the mode configuration as shown in Fig. 7(4). During the next stage of lasing operation the mode configuration undergoes a sequence of successively changing patterns. The onset of this behavior is noted as "beam breakup" in Fig. 6. The optical distortion of the window has become quite severe at this point, as shown in the final interferogram in Fig. 8. Further distortion of the window is accompanied by continued decrease in total power output until there is established a dynamic equilibrium of power density, mode configuration, and window distortion. No bulk heating of the window is observed.

Visual inspection of the window through a filter which blocks the scattered lasing radiation reveals a orange-red glow, appearing after the degradation starts, where the beam impinges on the inner-surface. The mode structure of the beam is delineated by intensity variations of this glow. Comparison with a similar fluorescent glow produced by argon laser radiation in glass suggests this is also a fluorescence. This effect has been noted elsewhere.[3]

If a laser with a degraded window within the optical cavity is allowed to begin lasing suddenly by covering and uncovering one of the mirrors then there results a rapid re-enactment of the above-described sequence of changes in the output beam characteristics. The section of the curve after the 20-minute point in Fig. 6 illustrates this. However, if the degraded window is removed from the system and reversed, no such rapid power decay occurs; the long-term decay only commences after the fresh surface has been exposed to the discharge for some length of time. Interferograms obtained with windows which had had both surfaces exposed showed that only the inner surfaces deformed.

In an effort to determine the cause of the gradual degradation of the windows tests were made with the shutter arrangement sketched in part B of Fig. 4. Prolonged operation with the shutter optically shielding the window from the line of sight of the discharge, while at the same time allowing the window to be exposed to the discharge tube environment, produced no discernible degradation of the window.

As mentioned above, the time scale of the window degradation cycle can vary widely. For a given discharge structure this decay rate is severely dependent on discharge current and other parameters. This general behavior pattern is evident in Fig. 9 where the decay in output power for two previously unexposed windows is presented. If we choose as the criterion for lifetime T the point at which the power has decayed to its apparent final infinite value plus $1/e$ the difference between the initial and final



DECAY OF LASER OUTPUT POWER DUE TO WINDOW
DEGRADATION FOR TWO DISCHARGE CURRENT VALVES

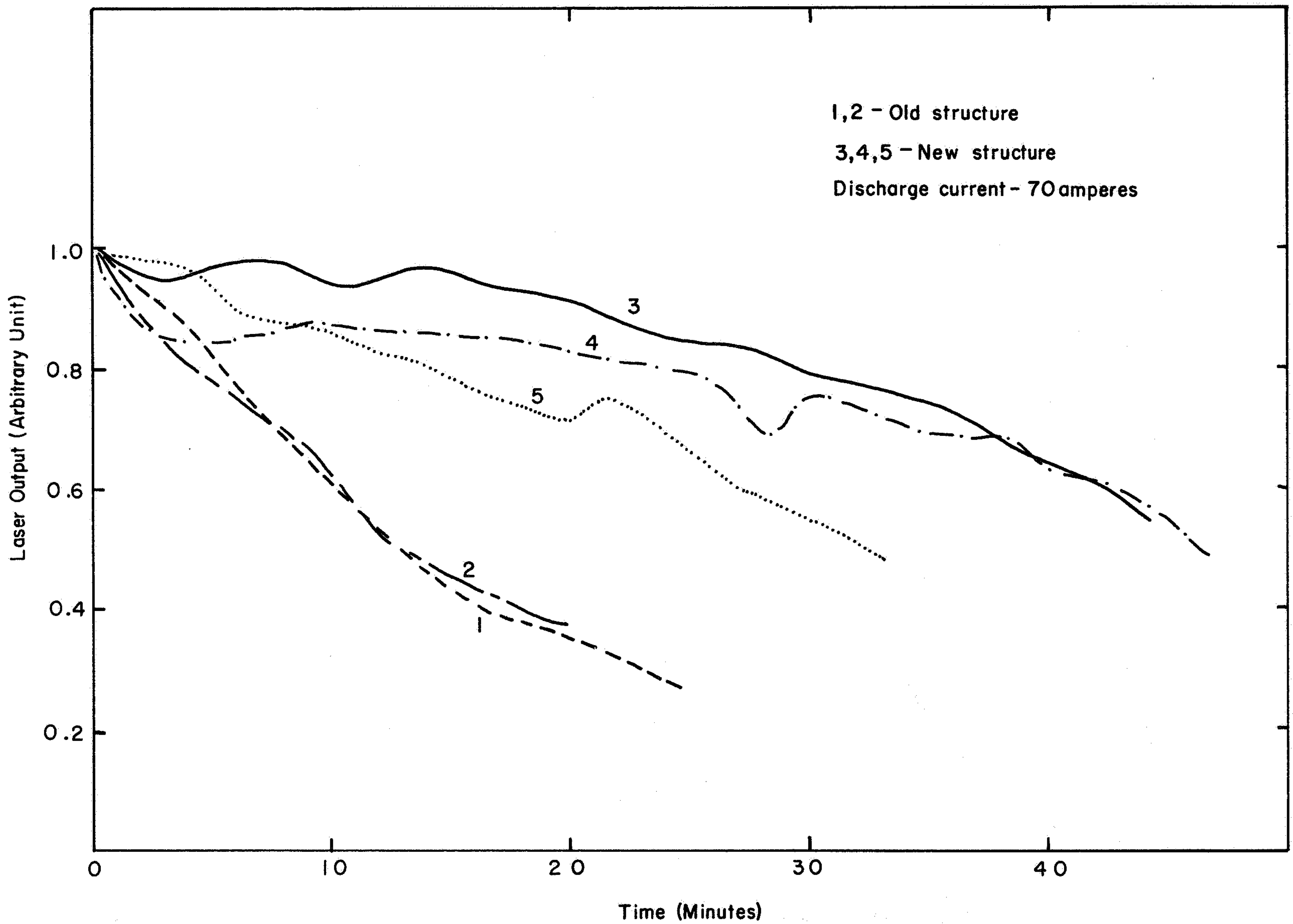
FIGURE 9

values, we find that these lifetimes are roughly consistent with the following relationship — $T \sim 1/I^{2.8}$ where I is the discharge current.

Aging of the Structure

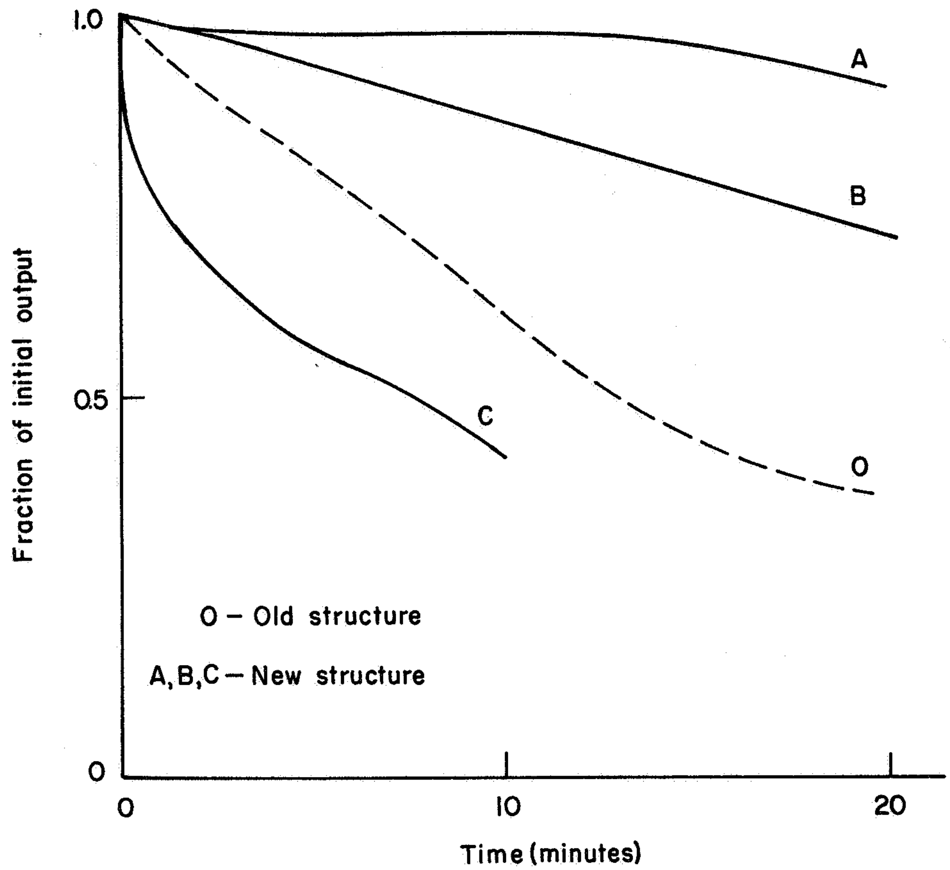
Another factor influencing the window degradation rate became evident when the discharge structure of the principal laser was replaced following a break in the bore of the initial structure. A substantial decrease in the decay rate was observed with the new structure, as compared with what had appeared to be the relatively stable rate of the old structure. In Fig. 10 normalized plots obtained with each structure are compared. Run 1 was obtained with the old structure just prior to tube failure, while run 2 was made a year earlier when that structure had been in operation a few months. Curves 3 and 4 represent runs made soon after installation of the new structure, and curve 5 a run made a few weeks later. The increase in the decay rate of run 5 compared to the earlier runs 3 and 4 represents a structure aging effect which is better shown in Fig. 11. Here runs 1, 3, and 5 (relabelled O, A, and B respectively) are compared with an additional run C obtained six week after run B. It appears that the older the discharge tube the easier it becomes to induce degradation of fresh windows. It should be noted that during that six-week interval many hours of 70 – 100 A operation were logged, much in contrast to the history of the earlier structure where such operating levels were quite limited in duration. This no doubt is related to the reasons why the earlier structure exhibited such an apparently stable and history-independent, damage-inducing capability.

A simple, qualitative test to determine the extent of window degradation with respect to a given operating level of a laser is to observe the beam geometry and power immediately after the onset of oscillation. That portion of the plot in Fig. 6 after the 20-minute mark represents the effect of a badly degraded window on laser output. This test was used as a criterion to evaluate the effect of window exposure to the nonlasing discharge. Observations made with a number of windows yielded somewhat inconclusive results. In most cases, at medium and low current, exposure to the discharge only was sufficient to degrade thw window to about the same extent as a similar exposure to the discharge and beam simultaneously. However, in a few cases, discharge exposure runs produced little or no effect on the condition of the windows. These tests were performed with the first discharge structure under conditions represented by curve 1 of Fig. 10. More recently, a variation of this procedure was tried with the new structure when the high degradation rate (represented by curve C of Fig. 11) was occurring. In order to further discriminate between the presence or non-presence of the beam, prior window exposure was made at a higher discharge current (90A) than that (70A) used in the earlier tests. Figure 12 shows the relative effects of a 7-minute exposure to a 90A discharge, lasing and nonlasing, on operation at the 70A level. In this case there was evidently quite a difference between the lasing and nonlasing situations. The presence of the laser beam seemed to increase the damage rate significantly.



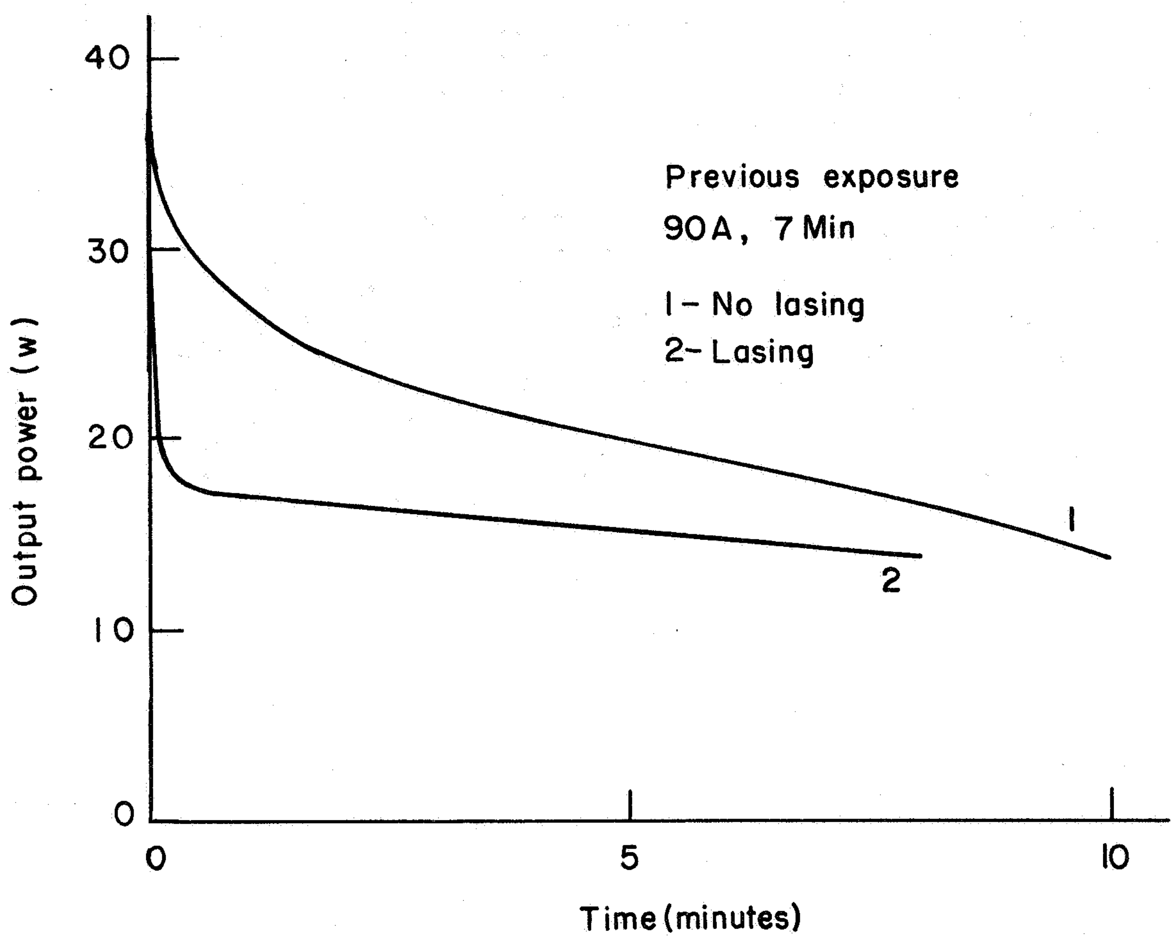
COMPARISON OF DECAY RATES OF LASER OUTPUT DUE TO WINDOW DEGRADATION FOR OLD AND NEW DISCHARGE STRUCTURES.

FIGURE 10



CHANGE IN OUTPUT POWER DECAY WITH
USE OF DISCHARGE STRUCTURE

FIGURE 11



OUTPUT POWER DECAY USING WINDOWS PREVIOUSLY EXPOSED TO LASING AND NONLASING DISCHARGE

FIGURE 12

When severe window degradation occurs, the laser output approaches a limiting value, as indicated in Figs. 9 and 12. The power-limited beam of plot 2, Fig. 12 was greatly reduced in area, with more than half of the beam-power concentrated in a narrow ellipse encompassing a core of extremely high-power density. This core of the output beam was well collimated and less than a millimeter in diameter.

A further insight into the effect of the laser beam on a window exposed to the discharge was gained by heating a window during a test run. Prior to the start of this investigation, degraded windows were heated to about 300°C for 1 hour after the discharge was stopped. No change in the state of degradation was noted. For this test a heating wire and monitoring thermocouple were fixed on a window which was fused to a quartz tube. The heated window was enclosed in an evacuated chamber in order to eliminate any optical distortion of the cavity due to heating the surrounding air. A cavity-end mirror and a window-viewing port were included in this structure. There was no reduction in the power decay rate as a result of heating the window to 400°C. In fact, observation of shearing interferograms indicated a possible increase in window distortion.

Other Lasers

A comparison was made of optical distortion of degraded windows among various laser structures. In addition to the 8 mm bore, principal laser which has a quartz discharge structure, two different 3 mm bore devices with pyrolytic graphite discharge structures were investigated. With each of these lasers distortion of degraded windows was noted when the optical power density approached several hundred watts/cm^2. The three lasers have similar cathode structures of oxide-coated tungsten mesh but the cathode area varies in the approximate ratio of 4:2:1. Insofar as could be determined, the cathode discharge current density necessary to produce decay times of less than a few hours was quite similar and equalled about 2A/sq in. of cathode.

Other Observations

Some windows which had been run through the cycle described above were removed from the lasers and thoroughly cleaned with non-abrasive solvents and detergents. Subsequent laser operation with these cleaned windows showed no change in their degraded condition. The only visual evidence of the surface condition of such exposed windows was obtained by noting the evaporation rate of a breath-fogged window; a fog pattern remained on the elliptical area exposed to the discharge after the rest of the surface cleared. In fact, the "breath test" proved to be a simple criterion of window degradation. Optical absorption and interferometric methods were found to be inadequate to indicate the presence of the surface degradation.

This resistance to cleaning was considerably reduced after exposure to room air for several days. Baking degraded windows in air at 300°C for 1 hour permitted them to be readily cleaned with the usual optical cleaning solutions (e.g., Kodak Lens Cleaner).

Spectroscopic analysis (by Jarrell-Ash Co.) of exposed window surfaces obtained to date were somewhat unsatisfactory but did give evidence of the presence of impurities (notably calcium) not found in the window substrate material. Impurities reported in excess of 0.1 percent were titanium and magnesium (0.1%—1.0%) and calcium (1.0% —10%).

Mirrors

Investigation of the power-handling capability of dielectric layer mirrors has been limited in scope. The standard substrate used in this laboratory is a 1.25-inch diameter by 0.5-inch disc of fused quartz. A plano-spherical geometry with the spherical surface curvature accurate to 1/10 wave and finished for minimum scatter is specified.

High Output Power

One test evaluated coatings supplied from three vendors: Optics Technology (OT), Perkin-Elmer (PE), and Infra-Red Industries (IRI). The test was designed to study sustained high output-power capability as contrasted to ability to withstand high circulating cavity power density, which in this case approached 1 kW/cm^2 only. Each vendor supplied coatings, one fully reflecting and one partially transmitting, for a pair of 3.7 m radius-of-curvature substrates. These sets were run in an internal mirror configuration on the principal laser with a 90 A discharge current. The test duration was 1 hour total, using a 10-minute on, 10-minute off cycle. A summary of the results is as follows:

TABLE I. – TEST RESULTS FOR DIELECTRIC COATINGS

Vendor	Mirror	Reflectivity (%) 4880Å	Reflectivity (%) 5145Å	Peak Output (W)	Power Decay
OT	Front	83	84	69	15%, 10 min (cyclic)
	Rear	99+	99+		
PE	Front	83	83	63	15%
	Rear	99+	99+		
IRI	Front	89.5	93	45	< 10%
	Rear	74.5	99.7	15	

The OT coatings were run at 80A for 1 hour previous to this test. Heating of the OT coatings or, more likely, the fully reflecting coating of the pair which developed a darkened area where the beam was located, is indicated by the cyclic behavior of the power decay. Visual inspection of the PE coatings as-received showed a lineage structure present. The IRI coatings had a speckled and foggy appearance and showed more surface scatter than the others. There was no observable beam shrinkage.

Bulk Heating

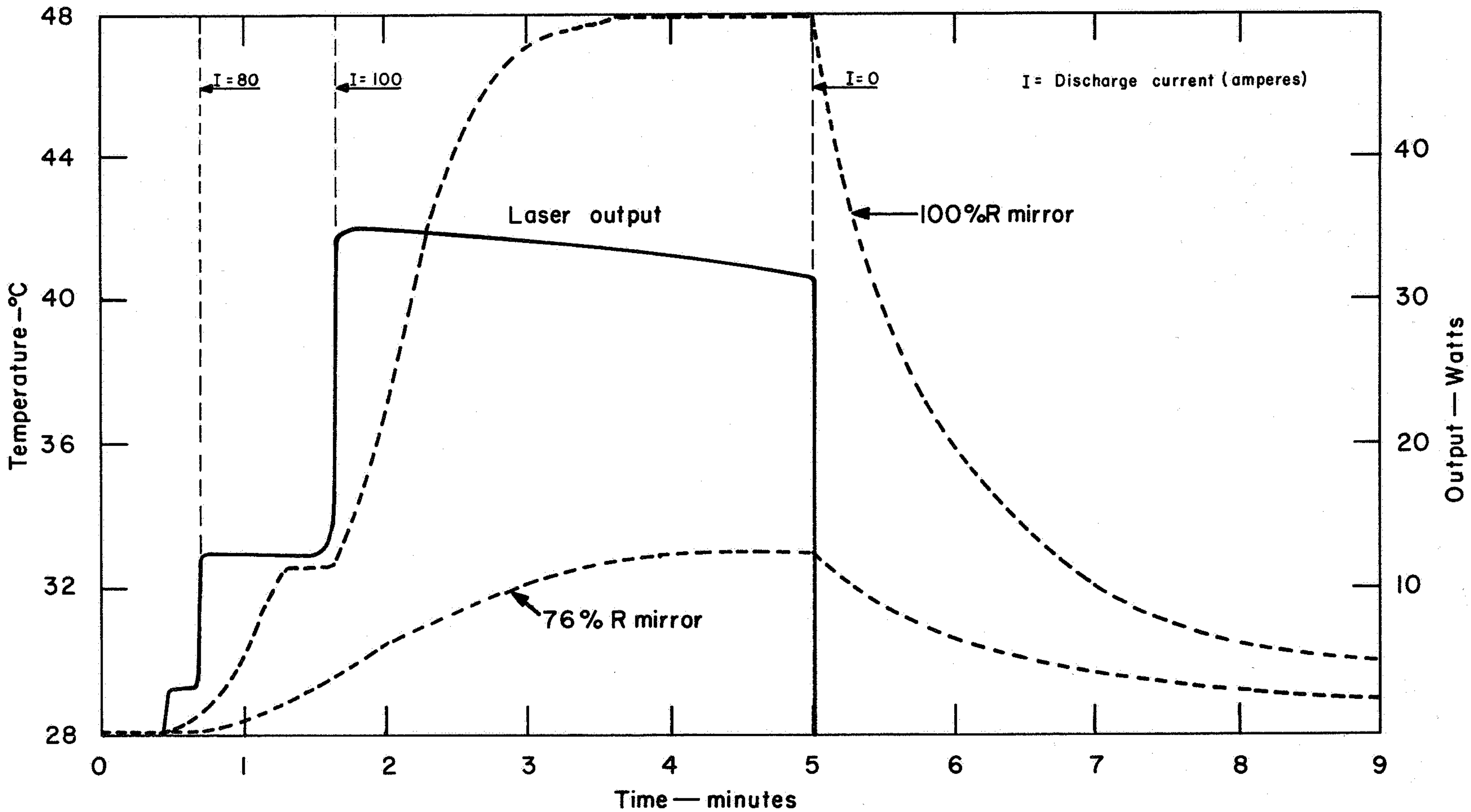
An attempt was made to study the effect of reduced circulating power loading on internal mirrors. Output coupling values of 34 and 24 percent were tested using 10 m radius substrates which were only 0.75-inch diameter by 0.25-inch thick. This configuration was much more sensitive to heating than the larger, shorter-radius standard geometry. No significant heating was observed with the 34 percent coupling, since only moderate power could be realized. Operation with the 24 percent coupling produced power levels sufficient to heat the mirrors enough to critically change this geometry. The bulk temperature and power output behavior at high discharge currents is plotted in Fig. 13. (Note: The output power values in Fig. 13 should be multiplied by about 1.5.)

The "breath test" revealed a changed surface condition over the circular area exposed to the discharge on many of the mirrors after high discharge current operation. On some of these mirrors a second circular area corresponding to the beam size was readily discernible within the larger circle.

DISCUSSION AND CONCLUSIONS

A prime objective of the present program was to identify the mechanism by which the Brewster's angle windows were being damaged in high-power ion gas lasers. At the onset there appeared to be at two likely possibilities: 1) surface damage to the window by the ultraviolet generated in the discharge, and 2) deposition on the window of material released within the discharge structure from the electrodes or walls by the erosive action of the high-power discharges involved. Much of the experimentation to date has been designed to assess the relative importance of these two possible mechanisms.

While many of the experiments were inconclusive with respect to this question, evidence is now accumulating strongly suggesting that the dominant process is in fact the deposition of a contaminating absorbing layer on the inner surface of the window and that these contaminants are most probably originating primarily from the cathode and not from the walls of the discharge structure.



BULK TEMPERATURE OF END MIRRORS MONITORED DURING LASER OPERATION.

FIGURE 13

It is clear that we are dealing with a surface degradation on the inner side of the window, which is exposed to the discharge; the "breath test," the restoration of the flat by surface cleaning processes, the observed deformation of the inner side only, the additional aging process required when a flat degraded on one side is reversed, and the spectroscopic analysis of the exposed and unexposed surfaces, all unambiguously indicate the presence of a surface film of some sort. The over-all "aging" process associated with the damage phenomenon is consistent with a gradual buildup of a contaminating film. The spectroscopic indication of significant amounts of calcium in this film points to the cathodes as the main source of the trouble. This is further confirmed by the preliminary apparent correlation between the rate of window damage observed in three different lasers and the current load in amperes per unit area of cathode.

There are several aspects that suggest that these films are tightly bonded to the surface: perhaps in a metallic form since oxidation appears to be necessary to remove the film. Freshly damaged windows or those baked out in a vacuum environment proved not to be susceptible to non-abrasive cleansing techniques. Simply leaving them exposed to the air for several days or baking them in air led to easy and total restoration by means of the same previously ineffective non-abrasive techniques. This suggests conversion of the contamination to a less tightly bonded oxide form. Some sort of reactive bonding to the surface is also indicated by the fact that heating the window either directly or via the laser beam while exposed to the discharge generally led to higher damage rates. Heating the windows could hardly increase the deposition rate but could significantly enhance adsorption processes or chemical bonding surface reactions which might be going on. This additional effect of the laser beam on the surface film deposition is perhaps best illustrated by the "breath test" results on the mirrors. There was a general (disc shaped) film where the mirror had been directly exposed to the discharge, as well as a clearly distinguishable secondary spot where the laser beam had been. There was evidently a general deposition of film, but the laser beam influenced the local character of this film.

Our experience with the new principal laser, which indicated that the rate at which new windows could be damaged was greatly dependent upon the past history of the laser, leads us to consider a multi-step process for the film deposition. It would appear that as the tube is operated more and more material is transferred from the cathode to the walls of the discharge structure. It is then revaporized by the discharge and ultimately finds its way to a window or mirror. The rate at which damage can be induced is, therefore, dependent upon how much "junk" has accumulated within the tube due to the past history of operation.

If the window damage was primarily due to the influence of the uv generated by the discharge, the rate should depend upon the instantaneous plasma characteristic of the discharge. It is, therefore, difficult to see how we can reconcile this with the observed history dependence of the damage rate. The one experiment which seemed to support the uv hypothesis showed that when the window could not "see the discharge" it did not become noticeably degraded.* However, this may be only an aspect of the laser beam enhancement of the damage rate. The shutter did prevent the laser action, and it is possible that this was the reason for the low damage rate observed.

We cannot rule out the effects of the uv completely on the basis of our experiments although the evidence is overwhelmingly in favor of the dominant role of deposition. In fact long term uv-induced polarization of windows by ion gas lasers has been observed.[4] We ourselves noted obvious polarization of a salt (NaCl) window used in one of the experiments. NaCl is of course particularly susceptible to the generation of uv-induced color centers.

Having established the existence of a growing film on the "damaged" optical elements the over-all behavior of the total laser is relatively easy to understand. This film is evidently absorbing in the visible; the laser beam, therefore, heats the inner face of the Brewster's angle window or mirror. As this inner face is exposed to a low-pressure environment, little heat is lost through this face and even very small absorptions can produce a significant increase in temperature in the immediate neighborhood when that part of the inner surface is illuminated by the laser beam. These localized temperature rises via thermal expansion and the temperature dependence of the optical index of refraction lead to the observed deformation of the windows. The result is that with time at a given current level the windows tend to absorb more and more energy from the laser beam and to become increasingly lenticular. The direct insertion loss due to this absorption, which is too small to be detected by straightforward techniques, no doubt has little effect on the performance of the laser. However, the lenticular distortions of the Brewster's angle windows can have severe effects. The introduction of a lens-like element into the optical cavity can produce significant changes in the optical configuration leading to drastic alterations of mode size, number, and stability. Because the temperature distribution will roughly follows the laser mode pattern (although smoothed out) we see that near the center of the mode the window deformation has little effect on the modes. However, as we move off the laser beam symmetry axis the inevitable temperature gradient produces deformations which tend to defocus the modes passing through the portions eventually suppressing them. Thus as the film absorption becomes significant, the first effect is to lead to a suppression of the modes on the outer edge of the laser beam and the pattern shrinks.

Actually because the windows are planed at Brewster's angle in the optical cavity, strong astigmatic effects are produced. If a lens of focal length f_o is placed at the Brewster's angle with respect to a beam of light the focal lengths in the plane perpendicular to the axis around which the lens has been rotated is reduced to:

---

*Discussed on page 12 of this report; the experimental setup is shown in Fig. 4.

$$f_{\perp} = \frac{1}{(n+1)\sqrt{n^2+1}} \; f_o$$

which for fused silica ($n \simeq 1.463$) reduces to

$$f_{\perp} \simeq 0.23 \, f_o \quad .$$

In the plane parallel to the rotation axis the focal length becomes

$$f_{\parallel} = \frac{\sqrt{n_2 + 1}}{n+1} \; f_o \quad ,$$

$$\simeq 0.72 \, f_o \quad .$$

Thus the effects of the distortions are greatly magnified by the angle of the window, and we expect to see strong astigmatic effects since $f_{\perp} \sim 1/3 \; f_{\parallel}$. The modes in the plane corresponding to $f_{\perp}$ are most strongly suppressed; thus we expect, as the distortion effects become stronger, to see the laser beam cross section become elliptical with the long axis parallel to the axis of rotation with an axis ratio of about 3 to 1. This corresponds roughly to what is observed at intermediate damage levels.

Eventually as the distortion phenomenon becomes even more severe, strong self-limiting effects set in. A well-established mode will distort the window precisely where it is most intense, which leads to strong defocusing and hence increased loss for that mode. This tends to reduce the mode power, which alleviates the distortion a bit and a balance is established. The damage window begins to act as an effective power limiter. No amount of increased input power can push the output power above this self-limited condition. In practice the principal laser which has shown itself capable of more than 100 W under appropriate circumstances, limited itself to about 20 W output when operated with a badly damaged Brewster window (see Fig. 6).

Under some conditions this self-limited situation can be temporally stable; more commonly, however, a dynamic instability occurs in which the spatial mode pattern breaks up into some complicated combination of higher-order modes which fluctuate rapidly with time. This is evident in Fig. 6 where after the point labeled "beam breakup" the power fluctuates irregularly. The modes are evidently not only defocusing themselves but actually turning themselves off, leading to a dynamic interaction between the fluctuating thermal distortions and the cavity mode.

As we have pointed out, the mirrors develop films like those on the windows; they absorb some of the laser power and distort in a fashion similar to the windows. Just why the mirrors seem to be less sensitive to this type of damage is not entirely clear. However, a portion of the answer is certainly provided by orientation of the mirrors. As we saw above, the Brewster's angle tilt of the window makes the $f_{\perp}$ about 1/5 of what it would be if the window was perpendicular to the beam. Thus we would expect the windows to be about 5 times more effective in upsetting the optical cavity. Whether this gives the entire story is not yet certain.

REFERENCES

1. Paananen, R. A.: Progress in Ionized Argon Lasers, IEEE Spectrum, Vol. 3, No. 6, June 1966, p. 97.
2. Bridges, W. B.; and Halsted, A. S.: Gaseous Ion Laser Research, AFAL-TR-67-89, Hughes Research Laboratory, Malibu, California, May 1967, Section VII, pp. 211-277.
3. Bridges, W. B.: Personal Communication.
4. Parker, J. V.: Metal Aperture Ion Lasers, Paper presented at the International Electron Devices Meeting, Washington, D. C., October 19, 1967.

NEW TECHNOLOGY APPENDIX

After a diligent review of the work performed under this contract, now new innovation, discovery, improvement, or invention was made.